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Art. III.—*The Mineralogy of the Sand Fractions of Some Victorian Soils.*

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Introduction.

The study of the minerals present in soils has received comparatively little attention, although the results of such a study are important in connection with the origin, development, and fertility of the soil. To study the application of soil mineralogy to these problems, twelve Victorian soils were selected from areas with different geological characteristics. Five samples, including two profiles, were taken from Jurassic areas, two from Quaternary deposits, one from the Older Basalt, and four from the Newer Basaltic areas, including one profile of four horizons. This paper deals with the mineralogy of these soils, and with the methods found most useful for this type of work. Before the discussion of these methods, a brief outline of the general principles of soil formation is given.

Soil is the result of the action upon the parent material of various forces which cause the disintegration of the parent rock into individual mineral grains, and the further disintegration and decomposition of these grains. The rate of decomposition depends, among other things, upon the amount of surface exposed to weathering, and decomposition therefore becomes more rapid as the material becomes finer, until at a certain size, the particles are decomposed as fast as they reach that size by disintegration. For this reason, the primary minerals (orthoclase, plagioclase, augite, etc.) occur mainly in the coarser fraction of the soil and are rare in the fraction having a diameter of less than 0.002 mm. (Marshall, 1935 i.). Together with the breaking up of the original minerals, formation of secondary minerals takes place. These minerals, especially the clay minerals (beidellite $Al_2O_3.3SiO_2.nH_2O$; nontronite, $Fe_2O_3.3SiO_2.nH_2O$, etc.) are found mainly in the finer fractions of the soil, particularly in the fraction with less than 0.001 mm. diameter. There is, of course, an overlap in the size distribution of these two classes of minerals.

The relation to the parent material is shown by the primary minerals, while the nature of the secondary minerals depends more upon climate than upon parent rock. These secondary minerals make up, wholly or in part, the colloidal fraction of the soil, and this gives important characteristics to the soil profile. In some cases, the effect of climate is so great that soils developed from different parent materials, but under the same climatic conditions, show a general similarity; they are then classed as belonging to the same soil group (Podzol, Chernozem, etc.). In other cases, however, climate has not been able to obliterate the effect of marked textural or chemical differences in the parent rock. Both cases are shown excellently in the soil map of the U.S.S.R., where belts of podzol, degraded chernozem, chernozem, chestnut and desert soils follow each other from north-west to south-east as the climate gets steadily drier and hotter. At the same time, podzol tongues formed on river sand dunes project into the chernozem belt, and the chernozem occurs on calcareous marl within the podzol belt.

This paper deals mainly with the primary minerals of the soil. The investigation of the finer material requires special apparatus and technique, because most of the usual microscopic methods for the identification of minerals fail for particles smaller than 0.02 mm. diameter. Highly accurate determinations of refractive index are necessary, together with the use of the ultramicroscope and X-ray analysis if possible (Marshall, 1935 ii.). Apart from the difficulty of the methods, the information supplied by the secondary minerals relates to other problems than those considered here.

Important Aspects of Soil Mineralogy.

Soil mineralogy is important in connection with the following three subjects:

1. *The Origin of the Soil.*—The primary minerals give some indication of the parent material, and by comparison with the underlying rock, one can determine whether the soil has been formed in situ or whether foreign material has been added. Characteristic minerals may indicate the source of such foreign material (cf. Elder and McCall, 1936).

2. *The State of Maturity of the Soil.*—The degree of disintegration and decomposition of the minerals gives a measure of the maturity of the soil. A mature soil, i.e., one which has developed the profile appropriate to the climate, contains only the most resistant mineral species (see No. 11). Since resistant minerals can be of little use for plant foods, a mature soil under a high rainfall may well be agriculturally poor, even though its parent material was rich in the necessary elements for plant growth. A soil which contains unweathered grains of readily decomposable primary minerals must be immature. This immaturity may be due to geological youth, as in the case of the basaltic tuff of Mount Gambier, the soil on which contains olivine crystals 1 mm. in diameter, and abundant clusters of small fresh augite crystals. Immaturity may also be due to the fact that erosion of weathered surface soil has kept pace with decomposition (see No. 17).

3. *The Fertility of the Soil.*—The soil minerals are important also as a source of plant foods. This question has been dealt with by Vageler (1933), who states that—"the permanence of fertility in a soil varies with its content of minerals still liable to decomposition". While this may be especially true under the more rapid weathering of tropical climates, it must apply also to temperate climates. Some writers believe that richness or poverty in potassium often depends on the presence or absence of potassium minerals, which, it is thought, some plants can use directly as a source of potassium (Van Baren, 1935).

The value of a given quantity of a mineral depends on the amount of surface exposed to weathering or to plant roots. In the coarse sand, this is insignificant, and the coarse sand minerals are therefore important only as a source of supply of the finer fractions. The amount of surface is much greater in the fine sand and still greater in the silt, and the percentage of mineral in these fractions is therefore an indication of fertility. While the silt fractions have not been studied in this work, the presence of a mineral in the fraction of 0.02 to 0.04 mm. diameter shows that it exists also in the silt. The results given for the percentage of mineral in the fine sand are therefore valuable for indicating fertility.

Methods of Investigation.

COARSE SAND.

Qualitative mineral analysis may be used to give some indication of the parent material of a soil, but for the questions of degree of maturity and soil fertility, quantitative results are much more useful. The fraction of the soil coarser than 2 mm. diameter, the gravel, usually forms a very small part of the soil and consists of concretions of lime or of iron oxide, or decomposing rock fragments. For this reason, the quantitative analysis of these Victorian soils was done only on the sand fractions. The coarse sand, 2 mm. to 0.2 mm., usually consists of individual minerals. In the soils examined, the coarse sand contains only a few mineral species, as would be expected, since only those minerals which are resistant to both disintegration and decomposition could persist in such large grains in a mature soil. With a few exceptions, the coarse sand of the Victorian soils studied consists almost entirely of quartz. The coarse sands were examined under binocular and petrographic microscopes, and in a few cases where several minerals were present, an approximate quantitative estimate of composition was made by counting the number of grains of each mineral present in a sample of 200, using a divided stage.

FINE SAND.

The minerals in the fine sand (0.2–0.02 mm.) were identified by using the petrological microscope and the usual optical methods for grains, especially as set out by Fry (1933). Refractive index was determined by immersions in standard solutions, and double refraction was measured by a Berek Compensator, the thickness of the grain being estimated by focusing on a top and bottom facet and reading the distance between the two focal positions on the fine adjustment screw. Such determinations give approximate results only, but are often very useful. Optical character was determined when necessary, and in a few doubtful cases, the minerals were rubbed down to flat plates to permit identification. In all cases, comparison was made with standard mounts of known detrital minerals or crushed mineral fragments. The rarer heavy minerals were in some cases concentrated, for easier identification, by specific gravity separation in bromoform.

Note on Specific Gravity Separations.

Unfortunately, such separations into fractions having different specific gravity could not be used as a basis for quantitative work for the particular problems considered here. In the first place, it is difficult to get accurate results with specific gravity separations of fine material, since the effects of surface tension interfere seriously with the settling of the minerals. Hendrick and Newlands (1923 and 1925) and Hart (1929) aimed at dividing the minerals into three groups according to their specific gravity, and worked on the fine sand as defined by the British Classification, 0.2 to 0.04 mm., and Hendrick and Newlands state that the finer material does not give accurate results when treated in this way. The fraction from 0.04 to 0.02 mm. contains many important soil minerals, and in some of the soils described in this paper, valuable information would have been lost if it had been neglected. In more recent work, Elder and McCall (1936) have adopted the International Classification, and have made specific gravity separations of the fraction from 0.2 to 0.02 mm., but the writer has been unable to obtain satisfactory separations of the finer material by this method.

In the second place, division into the three groups used by these authors is insufficient for the purpose of this work. It is important to make distinctions between the rock fragments and light felspars which make up the first group, the quartz and heavier plagioclases of the second group, and the ferromagnesian silicates and accessory minerals of the third, since these minerals have very different values in the soil.

Specific gravity separations using tetrabromoethane and nitrobenzene have been carried out recently by Volk (1933), with an elaborate process aimed at removing the films of water and air on the grains, since these films interfere with the separation of the minerals. He separated the soil minerals into six groups, and claimed to have obtained extremely accurate results with material down to 0.0003 mm. diameter, but his groups fail to differentiate quartz from plagioclase. Since the specific gravity of quartz is 2.65–2.66, and the plagioclases range from 2.62–2.76, it is obviously impossible to use specific gravity as a basis for separation of quartz and some of the intermediate plagioclases, however accurate the process. Such a separation was necessary in the work carried out here, so specific gravity separations using heavy liquids were abandoned. Where the heavy minerals of the parent material include fairly stable primary minerals, a study of the heavy fraction of the soil may be sufficient for purposes of correlation (Carroll, 1931 and 1933). In this case the actual proportion of heavy to light fraction is not important, and accuracy of separation is not essential. Where the heavy minerals of the parent rock are unstable, the heavy fraction of the mature soil formed from it is likely to consist of foreign material (see Nos. 10 and 11), and no correlation with parent material or indication of degree of maturity will be shown by this fraction. In either case, since the heavy minerals form very small proportions of the fine sands, fertility cannot be estimated if the light fraction is neglected.

Quantitative Methods Used in This Work.

The quantitative method used in this work consisted of counting the number of grains of each mineral present in a definite sample, and measuring the average diameter of the grains. Statistical theory indicates that to give satisfactory results 500 grains of each sand fraction must be counted (see below), and the counting of such large numbers of grains by the usual method, using a subdivided stage or eyepiece (Fry, 1933, p. 31), is a tedious process. It is considerably quicker and easier to use a mechanical stage and traverse the slide, recording the nature of the grain passing under the crosswires by means of a chosen letter on a typewriter. The eyestrain involved is greatly reduced by this method, since only the mineral in the centre of the field is examined, and it is not necessary to look up from the microscope to record the identity of the grain. Time is also saved, since the letters may be typed with the left hand while the stage is moved with the right. If the minerals are readily identified, 500 grains may be recorded in about 45 minutes.

A line traverse made at random on a mixture of equal numbers of large and small grains will obviously cross more of the larger kind, causing an error in the result of the count. This was tested with a slide prepared from a mixture of large quartz grains and small zircon crystals. Counts were made using a subdivided eyepiece, as well as by the method of traversing outlined above, and the correct result was found by photographing the slide and counting all the grains on an enlargement. The results given by using the subdivided eyepiece showed good agreements with the actual numbers of mineral grains present, but with the traversing method, although the results agreed well with one another, the quartz grains were more likely to be recorded than the zircons. Measurements of the average diameter of the grains showed that the number of grains counted on a line traverse was proportional to the number present multiplied by the average diameter. Miss M. Barnard, then on the staff of the Melbourne University, was good enough to investigate this problem mathematically, and she found that the above result was obtained theoretically, if the mineral grains were assumed to be spherical.

The volume of each mineral in the fine sand is proportional to the number of grains present multiplied by the mean value of the cube of the diameters. It is therefore proportional to the number of grains counted on a line traverse divided by the mean diameter, and multiplied by the mean cube of the diameter.

These two required means were obtained by making a number of measurements with a micrometer eyepiece. To avoid the selective effect caused, as described above, by line traversing, all the grains coming within a band wide in comparison with their diameter were measured. The diameter of each individual grain was taken to be the mean of its longest and shortest diameters. No attempt was made to measure the thickness of the grains, although the focusing method (Fry, 1933, p. 74) was available, because the value given would be at best approximate, and the measurements would take a long time. Most soil minerals tend to approach the spherical during weathering, and the longest and shortest diameters were usually found to be close to one another. The fact that results using the mean of these two measurements agreed with Miss Barnard's theoretical results assuming the grains to be spherical, showed that no important error would be caused by neglecting to measure the thickness of the grains.

Measuring the diameter of the grains is a tedious process, and, if approximate estimations of volume are sufficient, may be omitted. In this case, the method of counting by line traversing gives a better indication of volume proportions than methods using a subdivided eyepiece, for if n represents the number of grains of the mineral present, and d the diameter of a grain, accurate volume proportions are given by $n.$ (mean d^3), counting on a line traverse gives n (mean d), while counting with a subdivided eyepiece gives n. Line traversing therefore makes some automatic correction for grain size without the necessity of measuring the diameter of the grains. The results of this work show that counts made on a line traverse give fair approximation to volume proportions if the minerals concerned are not of very different sizes. If the grain sizes differ greatly, and it is important to estimate small differences in volume, measurements of diameter and calculation of volume as n. mean d^3 are necessary.

Two figures for the amount of each mineral are quoted in Table I., (*a*) the percentage in the fine sand fraction, and (*b*) the percentage in the soil. As regards fertility, the percentage of the mineral as fine sand in the soil is the more valuable result. The leaching down of clay into the subsoil, which is common among the podzolised soils of Southern Victoria, does not affect the percentage of mineral in the fine sand (*a*), but it increases the percentage of mineral in the soil (*b*) in the upper horizons at the expense of the lower. For this reason, it is better to choose samples that have been taken from similar depths, when comparing soils from different localities. In the present work, the sub-surface has been taken, since the surface soil is usually contaminated by the addition of wind-blown material (see below).

Statistical Analysis of Results.

This method of calculating the percentage volume of any mineral in the fine sand of the soil, although free from errors of identification, involves the following uncertainties:—

1. In the counting of the grains. The standard error of a method such as the one used is given by the formula—

$$\text{s.e.} = \sqrt{p.q.n.}$$

where p = the fraction of the whole represented by the particular mineral.

$q = (1 - p)$
n = the number of grains counted.

e.g., for plagioclase in No. 10, 20 grains occurred in a count of 500.

$$\text{s.e.} = \sqrt{\frac{20}{500} \times \frac{480}{500} \times 500} = 4.4 = 22\,\%.$$

As in all work of this kind, the counting of 500 grains is a compromise. A smaller number would give unduly large errors for the important minerals, and any further reduction of error by counting a larger number of grains would involve extra work that would not be warranted by the improvement of results. The variation between counts on duplicate slides was found to be the same as the variation between counts made on the one slide, i.e., the sampling error in making the slide is not serious. These variations are what would be expected in dealing with samples of 500.

2. In the calculation of the mean value of the diameter *d*, the mean value of d^3, and the ratio of the latter to the former, the standard error of each of these means it taken to be—

$$\sqrt{\frac{\Sigma x^2}{n\,(n-1)}}$$

where x = the deviation of the individual value of d or of d^3 from the respective mean,

n = the number of grains measured.

This formula assumes a normal distribution for both d and d^3. The distribution of both these variables is in fact skew with a maximum occurrence near the lower limit of the fine sand, but no serious error will be caused by using the formula. The number of minerals measured in any one sample depended on the spread of the grain size and the importance of the mineral. To obtain reasonably small percentage errors, it was found necessary to measure 100 grains of such a mineral as quartz, which has a very wide spread of grain size, while for the small plagioclases such as occur in Nos. 8 and 9, 25 measurements only were made. The accuracy aimed at in this work must, of course, depend on the time available. Measurement of 100 grains usually takes about 60 minutes.

A further error is involved in dividing the mean of d^3 by the mean of d. The calculation of this error presents a complex problem, which may be avoided by assuming that the percentage error of the quotient equals the percentage error of d^3. This seems likely to give a maximum figure for the required error.

E.g., for augite in Table I., No. 17, working in units of .01 mm.,

Mean $d = 5.38$, standard error 0.29 (5.4%).

Mean $d^3 = 266$, s.e. 46.2 (17.4%).

Ratio of d^3 to d, 49.4, s.e. 8.7 (17.4%).

3. In the calculation of the volume as number of grains counted multiplied by the ratio just discussed. The error of a product is given by the formula—

$$\text{var. AB} = \overline{\text{A}^2}\ \text{var. B} + \overline{\text{B}^2}\ \text{var. A} + 2\ \overline{\text{AB}}\ \text{covar. AB.}$$

where $\overline{\text{A}}$ and $\overline{\text{B}}$ are the means of A and B, and var. and covar. stand for variance and covariance. Since the covariance of A (number of grains counted) and B (ratio of mean d^3 to mean d) seems likely to be relatively small, the simpler relation is used—

$$\text{var. AB} = \overline{\text{A}^2}\ \text{var. B} + \overline{\text{B}^2}\ \text{var. A.}$$

The standard error (i.e., the square root of the variance) has been found for each of the volumes and expressed as percentage of the volume.

E.g., for augite in sample 17,

$\overline{\text{A}} = 75$, var. A $= 64$.

$\overline{\text{B}} = 49.4$, var. B $= 75.7$.

AB $= 3705$, var. AB $= 75^2 \times 75.7 + 49.4^2 \times 64 = 664,850$.

s.e. of AB $= 815 = 22.0\%$.

4. To find the percentage volume of each mineral, the different volumes are added together, and the percentage of each is calculated in terms of the whole. This involves uncertainties in the addition of a number of variables, and a further uncertainty in the division of each one by the whole. While the former error can easily be calculated, no suitable formula is known for the error of a quotient in such a case as this. Failing such a formula, the error of the product nd^3 is given for each mineral.

These methods, however, only give the error of one sample. If we wish to determine whether this sample belongs to a particular soil type, or whether it differs from another sample, allowance must be made for the inherent variability of soil. No figures are available to indicate the variability of minerals within the one soil type, but it is likely that the standard deviation of mineral figures due to this cause is 10–20%, as is found with the chemical properties of the soil.

Where only one sample of a soil type is available, the error is estimated as—

$$\sqrt{(\%\ \text{s.e.})^2 + (20\ \%)^2}.$$

Where several samples, which are known on other grounds to belong to the same soil type, are available, the error can be worked out on the assumption that these are random samples of a single population.

Mineralogy of the Sand Fractions and Discussion of Results.

1. Soils on Jurassic Sandstones.

No. 1. Leongatha, S. Gippsland. 6–12″.

Coarse Sand.

Quartz.—Angular to sub-rounded, somewhat ironstained in cracks and hollows. Inclusions common, apatite, iron oxide, fluid.

Plagioclase.—R.I. close to 1.545 and optically negative, oligoclase. Grains rounded, generally clouded and somewhat altered.

Orthoclase.—Irregular grains, sometimes altered, but generally quite clear and fresh.

Rock.—Irregular fragments.

Fine Sand.

Quartz.—As in Coarse Sand.

Plagioclase.—As in Coarse Sand.

Orthoclase.—As in Coarse Sand.

Iron oxide.—Small irregular grains. Magnetite or ilmenite, alteration to leucoxene in some cases.

Tourmaline.—Small stumpy prisms with rounded terminations. Brown most common, some blue-grey.

Zircon.—Small grains, usually completely rounded. Some prisms with rounded terminations.

Apatite.—Small stumpy prisms, much corroded.

(?)Nontronite.—Irregular fibrous grains, often encrusting on the other minerals. See No. 11 for optical properties.

Sponge spicules, epidote, brown anatase and rutile also present.

No. 2. Near Beech Forest, Otway Ra. 4–8″.

Principal minerals similar to those of No. 1. Apatite, anatase, and rutile were not observed, and garnet and sphene are present.

No. 3. Merino, Western District. 0–4″.

Principal minerals similar to those of No. 1. The grains of orthoclase are larger and usually quite clear and unweathered. Epidote, anatase, and rutile were not observed, and biotite is present.

No. 4. Poowong, S. Gippsland. 0–4″.

No. 5. Ditto. 12–15″.

Principal minerals similar to those of No. 1. Anatase and rutile were not observed, and garnet and apatite are present.

No. 6. Strzlecki, S. Gippsland. 0–4″.

No. 7. Ditto. 18–24″.

Principal minerals similar to those of No. 1. Anatase and rutile were not observed, and garnet and apatite are present.

The parent material of these Jurassic soils is a felspathic sandstone or mudstone having similar characteristics in the three Victorian outcrops of the Strzlecki, Otway and Casterton areas. It consists of quartz, plagioclase, orthoclase, biotite and chlorite, in a fine ground mass (Richards, 1910 and Skeats, 1935). Rosiwal tests on two samples from Apollo Bay and Barramunga gave the following results:—

Apollo Bay.—Quartz, 11%; felspar, 25%; matrix, 64%.

Barramunga.—Quartz, 12%; felspar, 33%; matrix, 55%.

The orthoclase-plagioclase ratio of the rock could be determined only by chemical analysis. Some of the felspar grains are fairly fresh, while others show advanced decomposition. The occurrence of unusual minerals such as anatase, garnet and sphene in the soils, suggests that the study of the heavy minerals of the Jurassic rocks might give interesting information as to the origin of this series in Victoria.

The soils studied from these rocks show a remarkably high content of felspar, which occurs even in the coarse sand. Felspars are usually regarded as a comparatively unstable mineral group, the presence of undecomposed felspar in a sediment being taken as evidence of deposition very close to the source (arkose), or of arid or glacial conditions of deposition (Mackie, 1899). Also, as already stated, some writers think that plants can use orthoclase directly as a source of potassium. It would be thought, then, that small grains of felspar would be too readily soluble to persist in soils such as these, which have been exposed to considerable leaching since the Pliocene period (Hills, 1935). The felspars of the Jurassic rocks, orthoclase and acid plagioclase, are more stable than the basic plagioclases which occur in the Victorian basalts (Mackie, 1899), but the presence of such large amounts of these felspars, as compared with the almost complete decomposition of the labradorite in mature basaltic soils (see Nos. 10, 11, 12), seems to show either that the stability of orthoclase and oligoclase is greater than is generally imagined, or that these Jurassic soils are immature.

The two profiles from the South Gippsland area show no differentiation of horizons. There has been no appreciable washing down of clay from the surface, and the mineral composition of the soil is not significantly different in the different levels. This may be partly the result of the considerable artificial disturbance of the soil which takes place during the clearing of the land. This involves the grubbing out of tree stumps, scraping to level the resulting uneven surface, and ploughing before sowing the land down to pasture.

The soil from Beech Forest, however, was taken from uncleared forest country, and no artificial factors can be involved. Profiles have not been collected from this area, but the soil described and another sample from the same locality show a high percentage of felspar in the 4–8-in. level. The comparative immaturity of these soils appears to be due to erosion on a steep slope, and this factor must be concerned to an even greater extent in the cleared country of Gippsland and on the sloping areas of the Casterton district. The importance of the factor of soil erosion could be determined only by collecting numerous profiles from areas having different slopes and different vegetation. Up to the present time, such a detailed study has not been possible.

The relatively high fertility of these soils on Jurassic sediments appears to be correlated with the presence of the felspars in the soil minerals, orthoclase felspar being particularly important.

2. Soils on Quaternary Sands.

No. 8. Wannon Falls, Western District. 6–12″.

Coarse Sand.

Quartz.—Clear grains, generally somewhat rounded.

Buckshot.—Round polished grains of hydrated iron oxide.

Fine Sand.

Quartz.—Larger grains somewhat rounded, smaller angular. Usually clear, liquid inclusions common.

Plagioclase.—Grains all rounded, cloudy and too greatly altered for further indentification.

Iron oxide.—Magnetite or ilmenite. Extremely small and irregular grains.

Tourmaline.—Small irregular grains or rounded prisms, yellow to brown most common, some green.

Zircon.—Small rounded grains or prisms with rounded edges.

(?) Nontronite.—Yellow fibrous fragments, varying size.

Pale brown biotite and sponge spicules also present.

No. 9. Near Orbost, E. Gippsland. 4–14″.

Principal minerals similar to those of No. 8. A few much corroded prisms of apatite occur.

Very little is known about the Quaternary deposits which form the parent material of these soils, but they are thought to be largely alluvial or aeolian. The soil minerals are almost entirely of resistant species common to sedimentary deposits, but the presence of plagioclase was unexpected. The grains of plagioclase show great decomposition, and have probably been derived from neighbouring igneous rocks, the Western District basaltic areas in the case of No. 8, and the East Gippsland granodiorites in the case of No. 9. These granodiorites may also be responsible for the trace of apatite in the Orbost soil. Both these soils are infertile, and this may be correlated with the high quantity of sand, almost entirely quartz, which is present.

3. SOILS ON BASALT.

No. 10. Near Woorndoo, Western District. 12–24″.

Coarse Sand.

Quartz.—Rounded to sub-angular. Inclusions of apatite, zircon, rutile (sagenite webbing), and liquid.

Buckshot.—Round polished grains.

Plagioclase.—Irregular grains, decomposition advanced along cleavages.

Fine Sand.

Quartz.—Larger grains rounded, smaller angular.

Plagioclase.—Irregular grains, usually cloudy and decomposed but occasionally clear.

Iron oxide.—Magnetite or ilmenite. Small irregular grains.

Olivine.—Small clear angular fragments.

Tourmaline.—Small rounded grains and stumpy prisms with rounded edges. Brown and blue.

Zircon.—Small rounded grains and prisms with rounded edges.

(?)Nontronite.—Yellow to brown encrusting fragments, size variable.

Sponge spicules are also present.

No. 11. Macarthur, Western District. 18–40″.

Principal minerals were the same as those of No. 10, except that plagioclase was not observed in the coarse sand. The secondary mineral which has been recorded as (?)nontronite is common in the fine sand. In colour it ranges from pale yellow to deep red brown. The R.I. is between 1.570 and 1.670, and is close to 1.635 in most of the grains, agreeing with the R.I. for nontronite as given by Marshall (1935, ii). The mineral is fibrous in habit, often encrusting on other grains, so its double refraction was not estimated.

No. 12. Dixie, near Terang, Western District. 0–8″.

No. 13. Ditto. 12–18″.

No. 14. Ditto. 27–60″.

No. 15. Ditto. 60–76″.

Principal minerals similar to those of No. 10. The plagioclase grains appeared to be larger and less decomposed in the lower levels than near the surface. Small fragments of augite were also present, and appeared to be more common in the lower levels.

No. 16. Nilma, near Warragul, Gippsland (on Older Basalt). 10–20″.

Principal minerals similar to those of No. 10. Typical buckshot gravel is not present in the coarse sand, but decomposed limonitic material occurs. The grains of plagioclase in the fine sand are all small and extremely decomposed.

No. 17. Birregurra, Western District (immature soil on stony rise). 0–3″.

Coarse Sand.

Quartz.—As in No. 10.

Rock.—Fragments of decomposing basalt.

Plagioclase.—Clear irregular fragments. Labradorite.

Augite.—Irregular fragments, decomposing along cleavages. Light brown with titanium violet tinge.

TABLE I.—MINERALOGY

No.	Locality.	Underlying Rock.	Depth.	Coarse Sand.						
				Percentage of Soil.	Mineral Composition.					
					Quartz.	Rock.	Plagioclase.	Orthoclase.	Buckshot.	Percentage of Soil.
1	Leongatha ..	Jurassic Sandstone	9–18″	9	57	3	35	5	—	40
2	Near Beech Forest	Jurassic Sandstone	4–8″	2	54	15	29	2	—	15
3	Merino ..	Jurassic Sandstone	0–4″	0.3	Com.	Pres.	Com.	Pres.	—	35
4	Poowong ..	Jurassic Sandstone	0–4″	6	Com.	Pres.	Com.	Pres.	—	44
5	Poowong ..	Jurassic Sandstone	12–15″	11	Com.	Pres.	Com.	Pres.	—	44
6	Strzlecki ..	Jurassic Sandstone	0–4″	3	Com.	Pres.	Com.	Pres.	—	26
7	Strzlecki ..	Jurassic Sandstone	18–24″	4	Com.	Pres.	Com.	Pres.	—	27
8	Wannon Falls, Western District	Quaternary Sand	10–20″	38	Flood	—	—	—	Pres.	32
9	Near Orbost	Quaternary Sand	4–14″	58	Flood	—	—	—	Pres.	28
10	Woorndoo, Western District	Newer Basalt	12–24″	1	Flood	—	Tr.	—	Tr.	9
11	Moyne Falls, near Macarthur	Newer Basalt	18–40″	1	Flood	—	—	—	Tr.	5
12	Dixie, near Terang	Newer Basalt	0–8″	6	Flood	—	—	—	Rare	49
13	Dixie, near Terang	Newer Basalt	12–18″	11	Com.	—	—	—	Com.	38
14	Dixie, near Terang	Newer Basalt	27–60″	4	Flood	—	—	—	Rare	20
15	Dixie, near Terang	Newer Basalt	60–76″	2	Flood	—	—	—	Tr.	15
16	Nilma, Gippsland	Older Basalt	10–20″	2	Flood	—	—	—	—	21
17	Birregurra ..	Newer Basalt, Stony Rise	0–3″	13	60	39	Tr.	—	—	27

NOTE.—The figures for minerals in the fine sand represent—1. Number of grains in count
3. Percentage mineral in fine sand. 4. Percentage mineral in soil. In some cases the
brackets are percentage standard errors.

OF SAND FRACTIONS.

Fine Sand.											
Mineral Composition.											
Quartz.	Plagioclase.	Orthoclase.	Iron Oxide.	Augite.	Olivine.	Zircon.	Tourmaline.	Apatite.	? Nontronite.	Rock.	Sponge Spicules.
248 (4) 74 (16) **55** (16) **22**	215 (5) 65 (13) **42** (14) **17**	11 (30) 43 (14) **1.4** (33) **0.6**	3	—	—	4	3	1	—	—	9
224 (5) 78 (16) **50** (17) **7**	235 (5) 71 (16) **47** (18) **6**	11 (30) 55 (14) **1.7** (17) **0.3**	9	—	—	3	3	—	11	—	4
253 (4) **51** **18**	141 (7) **28** **10**	59 (12) **12** **4**	6	—	—	1	1	—	7	—	32
276 (4) **55** **24**	149 (6) **30** **13**	36 (16) **7** **3**	11	—	—	6	—	1	10	—	11
224 (5) **45** **20**	170 (6) **34** **15**	52 (13) **10** **4**	13	—	—	2	—	—	27	—	11
254 (4) **51** **13**	181 (6) **36** **9**	54 (13) **11** **3**	3	—	—	1	2	—	1	—	4
221 (5) **44** **12**	189 (6) **38** **10**	59 (12) **12** **3**	5	—	—	2	2	—	15	—	7
463 (1) 128 (16) **99** **32**	14 (26) 12 (20) **0.3** (29) **0.1**	—	7	—	—	8	3	—	5	—	—
464 (1) 87 (17) **98** **28**	15 (25) 19 (23) **0.7** (34) **0.2**	—	4	—	—	6	1	1	2	—	7
456 (1) 50 (13) **96** **9**	20 (22) 25 (21) **2.1** (30) **0.2**	—	9	—	1	5	3	—	6	—	—
353 (13) 51 (13) **81** (14) **4**	35 (16) 14 (13) **2.2** (21) **0·1**	—	12	—	—	3	2	—	89 (10) 39 (19) **15** (22) **0·8**	—	6
438 (1) **88** **43**	14 (26) **3** **1**	—	8	—	—	5	1	—	9	—	25
427 (1)	17 (24)	—	15	—	—	2	1	—	26	—	12
408 (2)	26 (19)	—	14	—	1	3	1	—	45	—	2
416 (2)	34 (16)	—	15	1	1	6	1	—	24	—	2
458 (1) **92** **19**	7	—	12	—	—	3	6	—	8	—	6
226 (5) 67 (18) **58** (19) **16**	92 (9) 49 (18) **17** (20) **3·7**	—	70 (11) 25 (28) **7** (30) **1·8**	75 (11) 49 (17) **14** (20) **3·8**	18 (23) 17 (13) **1·2** (27) **0·3**	2	1	—	—	11 (30) 48 (22) **2·0** (37) **0·5**	5

of 500 2. Ratio of mean cube of diameter to mean diameter (units of 0·0001 sq. mm.).
second figure is omitted, and the values for (3) and (4) are then very rough. Figures in

Fine Sand.

Quartz.—As in No. 10.

Plagioclase.—Irregular grains, sometimes cloudy alteration, but usually quite clear and undecomposed.

Augite.—Irregular fragments, usually quite clear.

Iron oxide.—Magnetite or ilmenite. Generally as irregular fragments, more rarely as needles.

Olivine.—Sharp irregular fragments, usually colourless, sometimes showing alteration to iddingsite (typical of the basalt of this area).

Rock.—Fragments of extremely decomposed basalt.

Zircon.—As in No. 10.

Tourmaline.—As in No. 10.

Hyalite and sponge spicules also present.

In the case of these mature soils formed on basalt (Nos. 10–16), very few of the minerals found can have come from the underlying rock. Reference has been made to quartz in basalt (Fenner, 1915), and it is believed that quartz can crystallise from basaltic magma, but the quartz grains which occur in these basaltic soils contain inclusions of apatite, zircon, and rutile, showing that they cannot be authigenic. This is even more clearly the case with the grains of zircon and tourmaline which invariably accompany the quartz. These minerals, therefore, represent foreign material, and they occur also in numerous samples taken on basalt on the plains of the Western District and not described in this paper. This uniform distribution shows that they cannot represent pre-basaltic material picked up by the basalt flows during extrusion.

The occurrence of these minerals appears, therefore, to be due to the addition of wind-blown material to the soil during its formation, and the minerals are, in fact, similar to those which make up the aeolian Quaternary deposits. The total quantity of the foreign material is, however, so small that it would be absurd to say that the soils have not formed from basalt. Pfeffer and Hellmers (1934) mention the occurrence of quartz in the surface soil of basaltic areas in the Westerwald, Western Germany, and attribute this to the wind. From a formula given by Vageler (1933, p. 148) it appears that the grains in the coarse sand having a diameter of 2 mm. would be moved by a wind blowing at about 33 miles per hour, and those of 1 mm. diameter by a wind of 22 miles per hour. The fine sand particles would, of course, be transported still more easily.

The occurrence of these foreign minerals in the deepest samples taken on basalt appears to be due to the washing of sand down cracks which form in the dry season, associated with the drying of the heavy clay and with root systems. Sand has, in fact, been observed at deep levels in such cracks, in trenches dug in the Birregurra area.

Further evidence of the existence of wind transport is given by the presence, in all Victorian soils examined, of small broken fragments of organic remains, formed of isotropic silica. These have been identified by Mr. F. Chapman as spicules of the fresh water sponge *Spongilla,* in some cases resembling *S. cincrea* Bowerbank. Mr. Chapman states that a lacustrine phase favourable to the development of these organisms occurred in the Kalimnan, but that *Spongilla* is still an abundant living genus in swamp areas. These spicules appear in soils where *Spongilla* could not possibly live at the present time, and they therefore indicate wind transport. They decrease with depth far more rapidly than other wind-blown material, indicating that their addition to the soil was fairly recent, so that they have not had time to mix with the soil to any great extent. The occurrence of sponge spicules, particularly in the surface soil, has been recorded from many localities by Carroll (1931-2 and 1933-4).

These samples of soil taken on basalt indicate the effect of weathering and, for purposes of comparison, an example of an immature basaltic soil is included, from a soil survey of the Mount Gellibrand area near Birregurra (No. 17). The immaturity of this sample is due to erosion on a "stony rise", the slope of the rise causing the removal of the surface soil as fast as it becomes weathered. No. 17 contains large fresh grains of labradorite, augite, olivine, and rock, together with a certain amount of foreign material. It is a dark brown loam and, although very shallow and rocky, is a fertile soil.

On the basalt plains (Nos. 10–15), weathering has gone on to great depth and the unstable basaltic minerals are decomposed, the percentage of silt and clay increasing at the expense of the sand. In the mature basaltic soils the minerals in the sand consist almost entirely of added non-basaltic material, with only a trace of decomposed plagioclase to indicate the parent rock. The result is a grey clay of low fertility, and its chief difference from soils formed from the Quaternary deposits is not in the mineral composition but in the quantity of the coarse and fine sand.

This is well shown by the profile taken at Dixie (Nos. 12–15). This locality was marked as Newer Basalt on the geological map, but no rock was visible, and the profile showed no marked differences from profiles taken on the Quaternary. The influence of basalt is, however, shown by the greater amount and fresher appearance of the plagioclase and by the presence of augite and olivine, both unstable minerals, which are unlikely to survive transport. The high sand percentages, however, indicate that a large amount of foreign material has been added, and the soil may be regarded as intermediate between the normal soils on basalt and those on Quaternary deposits.

This profile indicates also the effect of depth upon the amount and mineral composition of the sand fractions. The fine sand decreases steadily from the surface downwards, owing to the washing down of clay and the greater amount of wind-blown sand in the surface horizons. (The coarse sand contains buckshot which is most abundant in the B horizon, and this explains the maximum at that level.) The decomposition of minerals may go on at different rates in the different horizons, and has probably gone on for longer in the upper than in the lower levels. This is indicated by the increase in the amount and freshness of fine sand plagioclase as depth increases. The iron oxide, being more stable, does not show this effect. The wind-blown material has been distributed through the soil by washing down cracks, though the sponge spicules are extremely rare in the lower levels.

The minerals of the soil on Older Basalt (No. 16) indicate a still more advanced state of maturity. The felspar grains are decomposed beyond exact identification, and are so small and rare that the sand may be regarded as almost entirely quartz. The comparative fertility of the red loams on these Older Basalts is due to factors which are not connected with the presence of valuable primary minerals.

Conclusions.

It can be seen that the study of soil minerals gives some surprising results. Igneous minerals occur in small quantity in soils derived from Quaternary sands, quartz is the most important mineral in the fine sands of soils formed from basalt, and sponge spicules, zircon and tourmaline are ubiquitous. From these results we may say that purely residual soils are rare, other factors besides the underlying rock being involved in supplying the parent material for any soil, although, in most cases, the added material is of little agricultural importance. The study of the soil minerals is useful in indicating these factors, and also gives valuable information as to the state of maturity of the soil and its probable fertility. The soils studied illustrate the importance of topography in determining the state of maturity of the soil.

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